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Long-term crop productivity response and its interaction with cereal markets and energy prices

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A B S T R A C T

Crop yields are endogenous as long as economic agents adjust to permanent changes in expected prices. The literature, however, does not offer a definitive value of how much yield would change in response to sustained price changes. To fill the gap, we use available scientific findings and data to estimate yield elasticities that enable agricultural commodity and food policy analysis. Using a world market model with short- to long-run yield response, we show the impacts of sustained energy price shocks on global cereal supply and demand. The results highlight substantial differences in quantity and price effects depending on the yield elasticities. These results demonstrate the need to recognize yield response when assessing impacts of energy prices or biofuel production on food uses or, more generally, on food security in the face of income and population growth, evolving dietary patterns, climate change implications, or other long-run pressures.

1. Introduction

An essential consideration for projecting long-term trends in food supply and for analyzing food crop policies over time is the degree to which crop yields respond to prices. Empirical estimation of long-run yield response has not overcome numerous obstacles, including weather-induced variability and decades-long processes of technological innovations. Consequently, food policy research might be biased towards high food price impacts of sustained yield or demand pressures. In this study, we apply existing economic theory and available data to develop a method for obtaining numerical estimates of long-run crop yield elasticities that can be used in food policy analysis. Moreover, we demonstrate the importance of long-run yield response for global cereal markets by showing that long-run cereal price impacts of biofuel demand are about half as large as reported in recent literature reviews. Because productivity response tends to be greater in developed country agricultural sectors, long-run food crop price impacts in response to energy price shocks to biofuel demand or supply costs are moderated in developed countries and developing countries open to trade.

Despite remarkable progress in agricultural productivity worldwide, worry over whether growth in the supply of food crops can keep pace with population and income growth persists. Historically, the intensity of such concerns rises and falls with spikes in food commodity prices. They became particularly acute in the context of rising biofuel demand. The Malthusian tone of the fuel-versus-food debate suggested that the future would be characterized by rising food prices and increasing hunger, particularly in poor countries where consumers draw a greater part of their calories from the cereals that served as feedstocks to biofuel production. These dire expectations were deflated when recession softened demand, rising petroleum supplies slowed biofuel demand growth, and yields broke records one year after another. The prospect of long-run food crisis driven by demand growth might have abated somewhat, but long-run food security concerns are now manifested in the climate change debate as well as in the context of rising income and evolving nutrition patterns.

Trends in crop production reflect trends in both area farmed and yield. However, almost all of the increase in global production levels witnessed since 1960 is due to increased yield, and not to trend increases in area farmed (Fig. 1). During this period, for example, global grain yield growth has been 1.5–1.9%, while total area planted to grain has grown by 0.4% (FAS, 2018). Data for a broader set of grains and oilseeds from the same source indicate that yield growth has been 0.2–2.0%, averaging 1.2%, while global total area planted growth has been 0.3% since 1971. For the United States, data suggest that trend output growth since 1948 can be explained by 1.7% productivity growth as there has been little or no growth in inputs (ERS, 2017).

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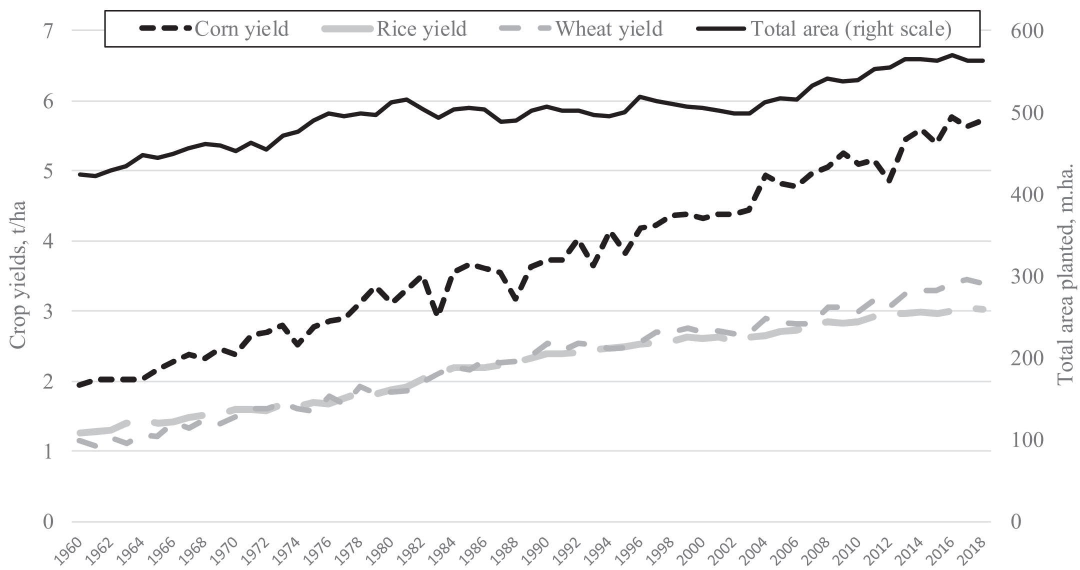

Fig. 1. Selected historical data representing global grain yield and area.
Source: FAS, 2018.

Accordingly, debates about future food security focus primarily on potential increases in crop yields (Lywood et al., 2009; Fischer et al., 2014). The evolution of crop yields over time depends on: (1) the quantity and quality of inputs farmers use and (2) environmental factors such as inherent soil quality, climate, and weather. While these second set of factors may be safely assumed exogenous to relative prices, economic theory dictates that market conditions matter both for the mix of inputs available to farmers and the choices they make.

There is little consensus about long-run yield responses to prices (Baldos and Hertel, 2013) or even how to represent expected prices (Nerlove, 1958), but the extreme cases appear implausible. Claims of immediate and vast yield response to output or input price changes would have to be reconciled with the slow-changing farming methods and crop patterns on farms and the steady, long-lasting yield trends. Claims of zero yield response to price changes imply that farmers will neither vary use of inputs nor change methods, no matter the time horizon. Zero yield response also implies that neither the cost of inputs nor their quality is responsive to output prices. It is difficult to argue that farmers and input suppliers would continue current practices unchanged even in the face of sustained perceived changes in relative prices. Ruling out extreme cases suggests that yield response is neither perfectly elastic nor perfectly inelastic, but that is hardly enough information to support food policy making.

In reality whether yield growth can be viewed as endogenous or exogenous to market prices depends on the length of run under consideration. For any practical length of run assumption, yield growth results from a combination of factors unrelated to price developments (e.g. weather) plus responses to price developments, since farm margins affect inter-annual production decisions. Three length-of-run assumptions are employed in this paper: short, medium and long. However, there are no generally accepted numerical counterparts to these conceptual time periods. In our review of previous studies reported below and in our own analysis we invoked, where possible, the following assumptions:

- Short run is immediate or up to two years;
- Medium run is three to five years; and
- Long run is more than five years and full productivity response to prices can extend many decades into the future, as discussed below.

However, strict adherence to this schema proved difficult in many instances as researchers frequently do not provide sufficient information to determine precisely the length of run to which their estimated coefficients apply.

1.1. Previous empirical analysis

Some recent studies detect a yield response to price. Table 1, adapted from Thompson et al. (2017), summarizes findings from a selection of such reports. Goodwin et al. (2012) estimate statistically significant, albeit small, yield response to price changes even in the very short run - within a marketing year. Their estimates of year over year response are, predictably, significantly greater. Empirical analyses assuming that yields are determined solely by weather-related events or technical progress implicitly take the view that yields do not respond to prices (Berry and Schlenker, 2011; Fischer et al., 2014; Schlenker and Roberts, 2008; Roberts and Schlenker, 2013), but these studies are less relevant to our study of long-run price effects on yields than those studies that explicitly test for price effects.

Huang and Khanna (2010) estimate non-zero short-run yield elasticities after controlling for county-level weather and land quality. Guyomard et al. (1996) estimate equations derived from multi-output, multi-input profit functions and find that price support reductions decreased crop yields in the EU. Basing their estimation on a profit function approach, as well, Arnade and Kelch (2007) detect important yield response to prices. Rosas et al. (2012) apply a profit function, with derived output supply and factor demands, that are applied to a combination of agronomic and market data and find statistically significant price elasticities for crop yields. Hertel et al. (1996) show that estimates of individual producer response to input price changes are less elastic than sectoral response because of compositional effects, namely the exit of producers who cannot respond effectively to a rising input price, implying that elasticities estimated at regional- or micro-level data are biased to be less elastic than the entire sector.

Peterson (1988) contends that time series estimation cannot discern expected long-run price from weather-driven transitory price changes, then advocates estimating yield response using cross-country comparisons to exploit persistent differences in price levels. Baldos and Hertel (2013) also emphasize the challenge of extracting long term supply response elasticities from annual data. Haile et al. (2016) combine annual and cross-country data to find, as did Peterson (1988), that implied long-run yield responses are often much greater than short-run responses. Goodwin et al. (2012), Huang and Khanna (2010), and Miao et al. (2016) also develop panel datasets, although at U.S. state and crop

Table 1
Estimated elasticities of crop yield response to price.

Source and region	Commodity	Data	Run*	Estimate
Peterson (1988)				
Multi-country	All crops	Cross-section,		
		119 countries	LR	1.19
Guyomard et al. (1996)	Soft wheat	Time series	SR	0.39
France	Maize	1970–92	SR	0.31
	Barley		SR	0.35
	Oth. coarse gr.		SR	0.22
	Rapeseed		SR	0.22
	Sunflower		SR	0.17
	Soybeans		SR	2.85
Arnade and Kelch (2007)	Corn	Time series	SR	0.20
Iowa	Soy	1960–99	SR	0.26
	Other grains		SR	0.44
Rosas et al. (2012)	Corn	Time series 1960–04	SR	0.29
Iowa	Soybean	field experiments	SR	0.61
Huang and Khanna (2010)	Corn	Time series 1977–07	SR	0.15
United States	Soybean	County data	SR	0.06
	Wheat		SR	0.43
Goodwin et al. (2012)	Corn	Time series 1996–10	SR	0.16 to 0.44
United States		Three states		
Miao et al. (2016)	Corn	Time series 1977–07	SR	0.23
United States	Soybeans	County data	SR	0.00
Haile et al. (2016)	Wheat	Time series	SR	0.17
32 countries		1961–2010	LR	2.08
	Corn		SR	0.09
			LR	2.35
	Soybeans		SR	0.15
			LR	1.95
	Rice		SR	0.04
			LR	0.16

Adapted from Thompson et al. (2017). Note (*): short-run (SR) response is understood to take up to three years and long-run (LR) response to take more than five years.

reporting district levels, and find a statistically significant corn yield elasticity and a statistically significant effect of soybean price on soybean yield after taking account of weather indicators. However, it is not clear if the use of panel data mitigates fully the risk that price variation in time series data obscures, rather than illuminates, long-run price expectations.

After reviewing the literature, Keeney and Hertel (2008) develop positive but inelastic yield responses that relate to a model that solves at a 3–5 year interval. Berry (2011) argues that these elasticities are too strong, possibly more than double the true response, but also sees a positive response in a limited amount of time and greater potential response over time as expected output prices rise.

1.2. Longer run considerations

Literature to estimate productivity effects of research funding is relevant to yield response in the very long term. We find only limited effort to study the drivers of private sector research and its consequences for productivity or yields. However, research into the productivity effects of publicly funded research and development helps assess the delays involved in long-run yield response on the assumption that the same sorts of lags associated with well-studied publicly funded research and development might apply as well to private investments motivated by price effects. More generally, apart from potentially trend-driven yields in the short-run, these efforts show that productivity is endogenous over time.

The role of private and public research and development funding in driving productivity has been emphasized (Wang et al., 2015) and at least some studies suggest potentially large effects from public funding after long delays (Alston et al., 2011; Gardner and Lesser, 2003; Hurley et al., 2014). This debate relates more generally to the theory of induced innovation (Hayami and Ruttan, 1971, 1985; Ruttan, 2002). The 2008 and 2011 crop price surges caused the food policy debate to turn to increased funding of agricultural productivity research and the surges appeared to motivate input suppliers, like seed companies, to step up their product development. Anecdotally, at least, it seems inappropriate to assume in long-run analysis that public or private research is exogenous and unresponsive to all price changes over all time periods, discouraging food market assessments with long-run yields driven by simple exogenous trends.

A relevant conclusion from the literature is that the delay between the application of research and the eventual productivity impacts is estimated to peak after two decades (Baldos et al., 2019) and to take up to 35 or 50 years to run its complete course (Alston et al., 2011; Huffman and Evenson, 2006). If we also consider how long prices must be sustained at a higher level before research funding is expanded in the first place, then even longer lags are possible between price signal and eventual yield increase. The implication is that there is a risk of bias in long-run food and crop analysis based on existing empirical yield elasticities estimated over shorter time periods that can reliably claim to capture only part of the full yield response.

2. Methods

With some exceptions, past studies estimate price elasticities of yield response that are positive and statistically significant. Consistent with theory, the few reported long-run elasticities are greater than short-run elasticities. Moreover, given limitations of data and methods, it is unclear that long-run elasticities reported in the literature take full account of all potential responses. However, applied simulation models typically do not reflect the potential for greater long-run yield response and the implications for food prices and consumption.

The method described here introduces long-run yield response to applied market and policy analysis (Fig. 2). First, we develop an approach to estimate yield response to price for a range of countries. This approach is grounded in two steps: one applies the theoretical

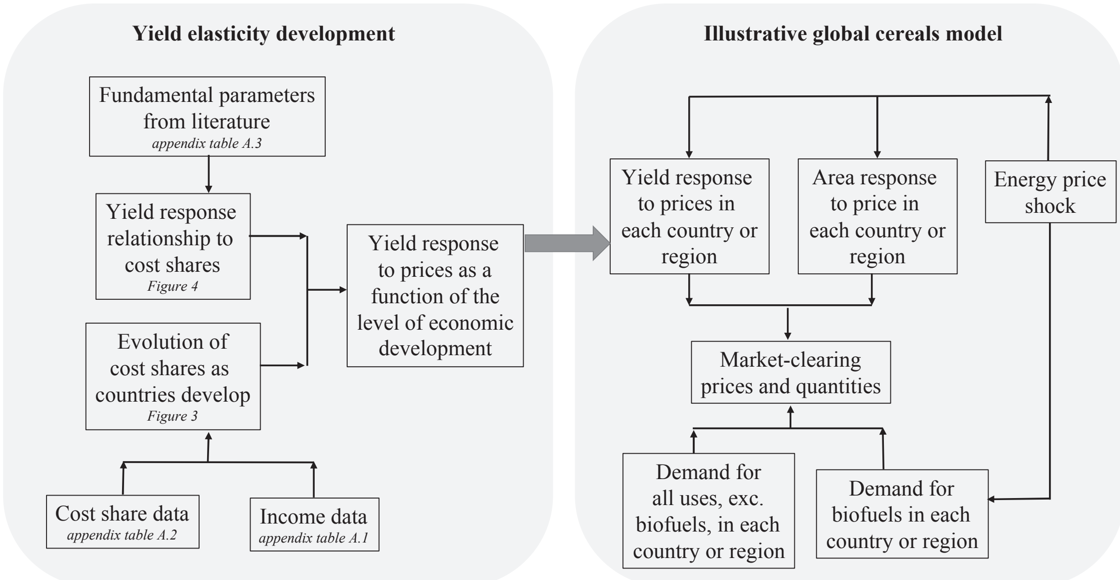

Fig. 2. Overview of method.

relationship between production cost shares and yield response, and the second step applies historical data to link economic development to the cost shares. Our method is summarized here and more detail is given in an appendix, so we associate the elements in the figure with tables that show key data and relationships. We then apply the yield estimates in a simulation model to show the implications of yield elasticity assumptions.

2.1. Yield response

We overcome the obstacle of sparse yield response estimates by relying on a widely used modeling method that allows us to model yield response by specifying a production function and the associated factor demand and supply equations (Floyd, 1965; Gardner, 1990; Hertel, 1989; Gunter et al., 1996; OECD, 2001; Martini, 2011). The supply equation derived from this general approach is

$$E_Y = \left\{ -[1\ 1\ 1] \times \begin{bmatrix} \partial_{1,1} - n_1/c_1 & \partial_{1,2} & \partial_{1,3} \\ & \partial_{2,2} - n_2/c_2 & \partial_{2,3} \\ & & \partial_{3,3} - n_3/c_3 \end{bmatrix}^{-1} \times \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \right\}^{-1}, \tag{1}$$

where $\partial_{i,j}$ are (symmetric) elasticities of factor substitution for three production factors, namely (1) farm owned factors (principally family labor), (2) an aggregate of purchased inputs and (3) land. Factor supplies are defined as n_i, and cost shares as c_i. Estimates for key elasticities of factor substitution and supply are available for a subset of countries (Abler, 2001; Martini, 2011; OECD, 2001; Salhofer, 2001).

This equation can be used to estimate the elasticity of yield response by holding land supply fixed, $n_3 = 0$ (Keeney and Hertel, 2008). Details are available in Appendix A.1, but can be summarized as follows. We develop a range of values for fundamental parameters from the body of literature (reported in Appendix Table A.3). These parameters relate to factor supply elasticities, and input substitution elasticities. A set of values for these parameters and cost shares determines the yield response to price. We draw from these ranges in Monte Carlo analysis to generate ranges of yield responses that are consistent with the fundamental parameters and cost shares. We then develop a reduced form relationship between a specific cost share and the yield elasticity. Specifically, we estimate a double-logarithm relationship between the cost share of farm-owned inputs, including all costs except for land, and the yield elasticities.

Factor supply that is not perfectly elastic embodies the cost of adjusting factor supplies in response to changes in their prices. These costs, and thus the associated elasticities, will be different for different factors. However, we make no distinctions among the various kinds of adjustment costs underlying the empirical estimates. These would comprise a complicated mix of increased utilization of variable inputs and investments, including in research and adoption of new techniques by way of example. And, that mix would be different for different lengths of run.

The length of run characterizing the yield response elasticities obtained using Eq. (1) reflect the adjustment period of the assumed elasticities of supply of the various factors of production. In many of the studies cited above and from which we obtained estimates of these parameters, researchers refer to an adjustment horizon of 3–5 years - what we defined earlier as a medium run.

The next step is to use the relationship represented in Eq. (1) and the available information to determine yield responses for a wider set of countries and, as well, to exploit this relationship to support forward-looking analysis of food markets and policies.

We can estimate the labor cost share of non-land costs as a function of per capita income based on available data. The factor shares data used for total factor productivity calculations indicate that the share of labor in all production costs, excluding land, has an inverse relationship with economic development, as measured by per capita GDP (Fig. 3). This relationship, once estimated, can be used to derive the labor cost share and then the purchased inputs cost share can be calculated recursively. The relationship between GDP per capita and labor shares in non-land costs is estimated as

$$\ln(Labor\_cost\_share) = a + b * \ln(GDPcap) + \varepsilon, \tag{2}$$

where $Labor\_cost\_share$ is the share of labor costs in all costs excluding land; $GDPcap$ is GDP per capita for selected countries; a is the constant; b is the elasticity of labor cost share with respect to GDP per capita; and ε is an error term. The coefficient on log of per capita income, b, is -0.09 and with a p-value of less than 1% when this equation is estimated using ordinary least squares.

Economic development is represented by gross domestic product (GDP) per capita (Table A.1). Farm-owned factor share is represented using labor shares of production costs, excluding land costs (Table A.2). GDP per capita data for 119 economies in 2011 were extracted from the

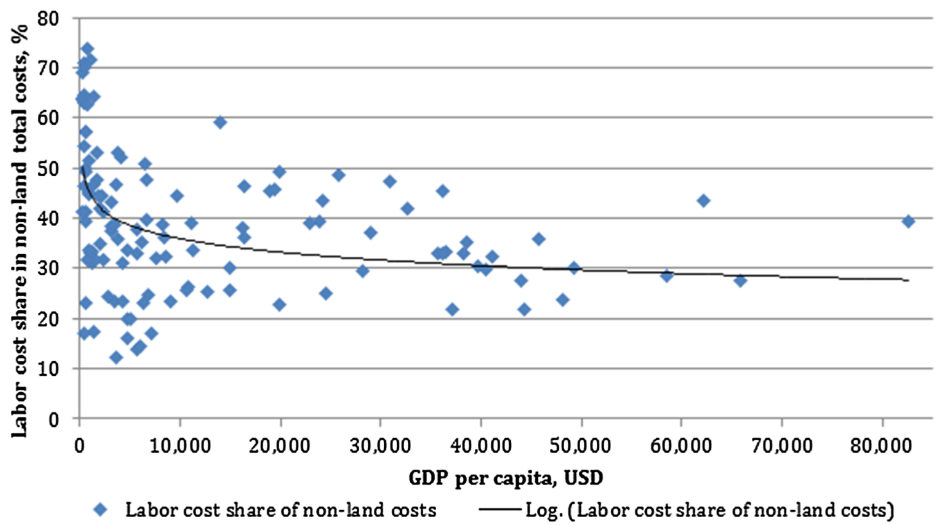

Fig. 3. Relationship between GDP per capita and labor share of production costs.
Sources: GTAP (2017) and World Bank (2016).

World Bank (2016). Costs were calculated as a sum of intermediate input costs for both domestic and imported goods, including tax payments, as well as skilled and non-skilled labor cost and capital cost in GTAP data (GTAP, 2017) and excluding land. The costs were summed for a range of commodities, including paddy rice, wheat, cereal grains, oilseeds, sugar cane and sugar beet, plant-based fibers, and other main crops.

In a second step we estimated a relationship between long-run yield elasticity and labor share of production costs. To reflect uncertainty regarding input supply elasticities, a Monte Carlo simulation method is used to estimate the implied long-run supply elasticity for a wide range of possible values. Specifically, we develop five hundred possible yield elasticities with regards to a farm-owned factor share, which is used as a proxy for labor (Appendix A.1). The results can be approximated using a variety of functional forms (Fig. 4). We trace several functions that can approximate the share of farm-owned factors in total costs, excluding land, to the elasticity of yield with respect to output price. As explained above, we use the double-logarithm functional form to, first, establish a link from per capita income to cost share and then from cost share to yield elasticity with respect to output price.

2.2. Experimental analysis and reduced form global cereals market model

Our experiments use energy price implications for cereal production costs and cereals use as biofuel feedstocks, but in practice one could consider the demand-side-only shock results to indicate the impacts of a policy focused on biofuel use. We investigate these supply and demand effects, which vary by country, separately and together.

With this objective, we use a global cereals market model and examine the implications of different yield response elasticities, following a common approach to assessing agricultural commodity markets (Binfield and Hennessy, 2001; Breen et al., 2005; Hoang and Meyers, 2015; Kim et al., 2013; Yu et al., 2011). The model is summarized as follows (for more details, see the Appendix A.2). The model has a representative developed country and two representative developing countries, a rest of world (ROW) aggregate, and global market clearing. Each country or region has equations for area, yield, production, biofuel demand, other demand, and a market-clearing identity. Key driving

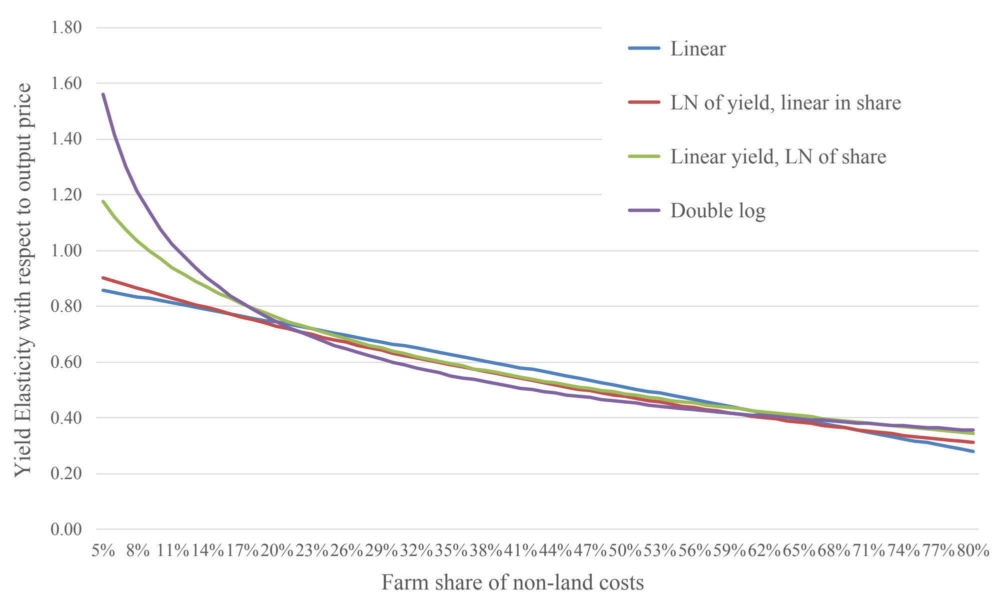

Fig. 4. Relationship of farm share of non-land costs to yield elasticity.
Source: authors' calculations.

forces include the domestic price and the price of petroleum-based fuel. For all but one region net trade is a residual of the market-clearing identity and domestic prices are linked to world prices. Cereal world prices clear trade at the global level.

In this reduced-form model, one developing country is represented as a case where trade is preset by policy at a fixed quantity of imports and there is no price transmission, so that the market-clearing equation in that instance solves for domestic price. This country also has no domestic biofuel market and the other developing country that is open to trade also has only a small domestic biofuel market. This isolated country is identified explicitly to represent one of the stereotypical cases: a developing country that has no biofuel market of its own and is isolated from world markets. The lack of integration with the world market might be driven by natural or policy factors. Particularly using comparisons to other cases, we can examine certain food policy implications relating to yield response for such a country.

Model elasticities for area response and demand are derived from the Aglink-Cosimo model (Araujo Enciso et al., 2016; Araujo Enciso et al., 2015; Dewbre et al., 2001; OECD-FAO, 2015; OECD-FAO, 2017). This model represents annual supply, demand and prices for the main agricultural commodities produced and traded worldwide. However, the model used here aggregates the separate cereals and countries into broad aggregates (Appendix Table A.4). The reduced-form parameters are derived from the full Aglink-Cosimo model such that, in principle, the analysis conducted here could be reproduced using the full version. These parameters implicitly include all the responses of the Aglink-Cosimo model, including effects in other commodity markets, such as livestock or dairy.

Model response is represented in three phases: short-run, medium-run, and long-run. The key distinctions are in terms of supply response. The short-run disallows any response in cereal yields or area planted, so results correspond to the immediate effect of a shock that occurs within a marketing year, for example. Medium-run supply response allows full area response as producers adjust the crop mix, but only one-tenth of the full yield response. This choice reflects the partial response possible in the span of a year or two, according to past studies. Long-run response maintains the area response and also introduces the full yield response outlined above, thereby representing the full array of responses by input suppliers and farmers to a sustained change in price signals.

3. Results

3.1. Yield response

Short-, medium- and long-run yield elasticities are derived based on the preceding method and the understanding that factor shares tend to vary systematically with level of development. As the supply of labor to agriculture in a developing country might have limited responsiveness to relative prices, with people shifting slowly into or out of agriculture, the greater role that this input plays in such countries can have implications for overall crop supply response. Conversely, purchased inputs that might tend to have higher supply response over time, such as fertilizers, pesticides and herbicides, and credit, tend to increase as a country becomes more developed.

Crop yields are estimated to be less inelastic in developed countries than in developing countries because of the larger role played by purchased inputs, including energy, in these countries relative to developing countries. The long-run yield elasticities were estimated for the representative economies: – a developed country (GDP per capita of USD 44,000), two developing countries (USD 1000) and a ROW aggregate representing the remaining countries (USD 3500). The estimated long-run yield response are 0.47 for the developing countries, 0.56 for the developed country, and 0.50 for the ROW.

The share of energy in the costs of cereal production is higher in developed countries, at 13%, than in developing countries, where the share is 1%. Developed countries can draw in more energy in comparison to developing countries that rely more heavily on relatively fixed factors of production. This greater role of purchased inputs, such as energy, also causes purchased input prices to have a larger impact on crop supply and food. These shares and responses have implications for the sensitivity of these markets to energy and fuel price shocks.

3.2. Crop market and price implications

The implications of yield responsiveness and the role of energy costs in cereal markets are explored using the market model. The implication of a one-time shock to energy price is examined in three steps: first, only cereal production costs are affected, second, the energy price jump affects only biofuel demand, and, third, the higher energy price affects both cereal production costs and biofuel demand. The initial impact is larger in the developed country because the energy share in production costs and the biofuel demand share are both larger there than in the developing countries.

An increase in cereal production costs tied to a 20% jump in energy prices causes higher prices and lower use, particularly in the countries that are linked to world markets (Table 2). These impacts grow over time, as both farmers and input suppliers are given more time to adjust. In the developing country open to trade, the medium-term area response is bigger than the medium-term yield response. In the long run, the growing yield impacts and consequently greater price effect reverse some of the directions of effects. This change of direction leads to higher yields in the developing country that does not trade – owing as well to the smaller share of energy in cereal inputs – and greater area planted to cereals in the developed country. The supply-side effects of an energy price shock tend to affect developed countries more directly because energy is a higher share of inputs. This large initial impact spreads to other countries through trade, and has growing and potentially reverse effects given greater long-run yield response.

The case where the energy price increase affects only biofuel demand shows the opposite pattern for price effects: price increase is high initially when demand shifts out and supply is fixed, but the price effects moderate as area responds and are much lower after allowing full yield response. The medium-term results suggest that an additional 6 million metric tons cereal use for biofuels, a 4% increase that accounts for 1% of total cereal production, causes a cereal price increase of \$4.33, or 2% (Appendix Section D). Calculated ratios of impacts of price and quantity for biofuels related to maize are +\$0.18 corn price per bushel for a billion gallons of ethanol, or +3.5% in the corn price per billion gallons of additional corn-based ethanol. These ratios are reassuringly similar to recent meta-analysis findings, specifically an average +2.9% per billion gallons (Condon et al., 2015) and \$0.15 per billion gallons (Thompson et al., 2016). However, the greater long-run yield response causes smaller ratios of +\$0.08 per bushel or +1.6% for an additional billion gallons of corn-starch ethanol. Moving from medium-run yields to long-run yields removes more than half of the price impacts of biofuels. Moreover, the long-run impact on world cereal area is about one-half as large as the medium-run increase because of greater long-run yield response.

The cereal market effects of an energy price shock taking into account production cost and biofuel demand impacts is substantially larger than the supply-side effects alone. The short-run price increase in most markets is caused by the sharply higher demand, without allowing any time for supply response. Medium-run supply response results decrease the price effect among countries tied to world prices by more than half. Although eventual yield response might be thought to further mitigate the demand shock, the long-run price rise remains substantial. The reason is the production cost effects, as the long-run yield response in this case takes into account both the demand-driven price rise and the cost effects. The developing country that is closed to trade and has no domestic biofuel demand is isolated from these shocks. Energy prices play little role in cereal production costs and no role in demand in such

Table 2
Energy price shock (+20%) effects on global cereal markets.
Source: authors' calculations.

Energy price effect through production cost				Energy price effect through biofuel demand				Production cost and biofuel demand effects			
Time of response	Short	Medium	Long	Time of response	Short	Medium	Long	Time of response	Short	Medium	Long
Developed country				Developed country				Developed country			
Area	0.0%	−0.1%	0.1%	Area	0.0%	0.9%	0.4%	Area	0.0%	0.7%	0.5%
Yield	0.0%	−0.1%	−0.5%	Yield	0.0%	0.1%	0.6%	Yield	0.0%	0.0%	0.1%
Price	0.0%	1.1%	1.7%	Price	7.5%	2.2%	1.1%	Price	7.5%	3.3%	2.7%
Developing country, integrated with world market				Developing country, integrated with world market				Developing country, integrated with world market			
Area	0.0%	−0.2%	−0.2%	Area	0.0%	0.2%	0.1%	Area	0.0%	0.0%	−0.1%
Yield	0.0%	0.0%	−0.1%	Yield	0.0%	0.1%	0.4%	Yield	0.0%	0.1%	0.4%
Price	0.0%	1.0%	1.5%	Price	6.6%	1.9%	1.0%	Price	6.6%	2.9%	2.4%
Developing country, not integrated with world market				Developing country, not integrated with world market				Developing country, not integrated with world market			
Area	0.0%	−0.1%	0.0%	Area	0.0%	0.0%	0.0%	Area	0.0%	−0.1%	0.0%
Yield	0.0%	0.0%	0.1%	Yield	0.0%	0.0%	0.1%	Yield	0.0%	0.0%	0.0%
Price	0.0%	0.0%	0.4%	Price	0.0%	0.0%	0.1%	Price	0.0%	0.0%	0.3%
World totals				World totals				World totals			
Area	0.0%	0.0%	0.1%	Area	0.0%	0.3%	0.2%	Area	0.0%	0.3%	0.2%
Yield	0.0%	−0.1%	−0.3%	Yield	0.0%	0.5%	0.8%	Yield	0.0%	0.3%	0.5%
Use for biofuel	0.0%	−0.2%	−0.4%	Use for biofuel	2.3%	3.7%	4.0%	Use for biofuel	2.3%	3.5%	3.6%
Other use	0.0%	−0.1%	−0.2%	Other use	−0.8%	−0.2%	−0.1%	Other use	−0.8%	−0.4%	−0.3%

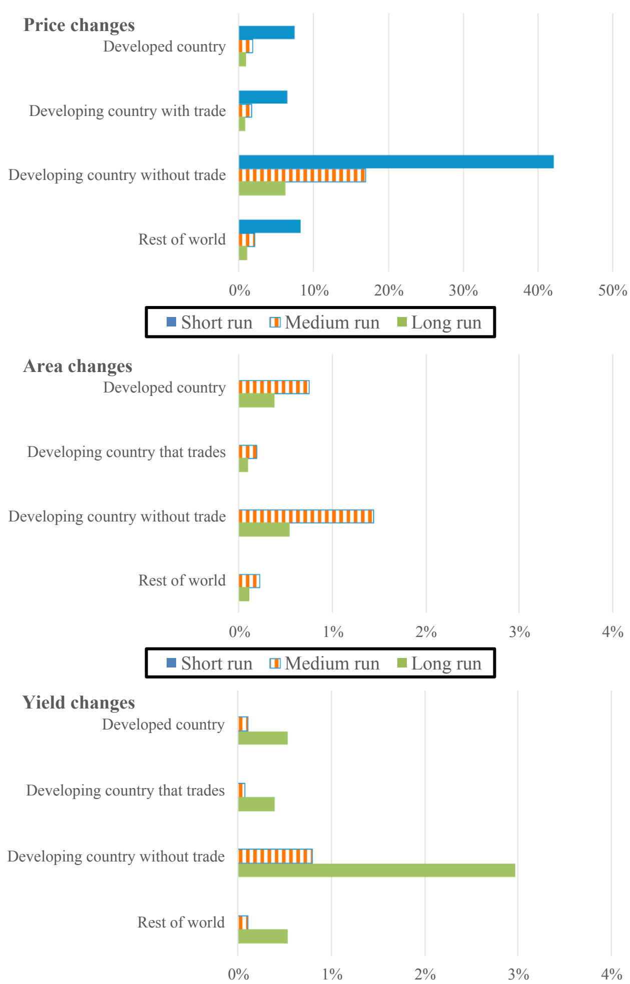

Fig. 5. Crop price, area, and yield changes associated with sustained demand increases depending on supply response.
Source: authors' calculations.

cases. Such a market might be more susceptible to other shocks, however, such as a domestic yield or area shock.

Sustained growth in demand was seen during the price surge of 2005–2007 as a driving force during the price surge and a reason for rising real prices in the future. We use the model to show the role long-run yields play in assessing price impacts of sustained income and population growth, that causes annual demand growth of 1.0% in the developed country, 2.5% in developing countries, and 1.5% in the rest of the world (Appendix Table A.8).

Results demonstrate the implications of ignoring yield response over a long time period to assess the impacts of sustained demand growth outlined above (Fig. 5). Short-run assumption of no yield or area response causes the largest price effects, but is easily the least plausible assumption for long-run analysis. Medium-term supply response that rests on area expansion at least as much as on higher yield, mitigates price increase substantially, but traded crop prices grow at about 2% per year and the crop price inflation in the isolated developing country is in the double digits. Allowing long-run yield response reduces annual price growth to about 1% for countries that trade. The developing country that does not trade suffers larger price effects in all cases: demand growth in the absence of any supply response would lead to a steep price to ration staple food consumption, and price effects are mitigated but remain large even with longer-run response owing in part to the lower yield response in developing countries as compared to developed countries. In contrast, the developing country that allows trade experiences much smaller growth in price, suggesting that the ability to draw on global supply response, particularly the higher response of developed countries, could help offset domestic demand growth in a developing country. In all cases, long-run crop price growth rates can be reduced by approximately one half if long-run yield response is used instead of medium-term responses when assessing future demand growth.

4. Conclusions

Food policy makers frequently face decisions requiring a long-term view of the determinants of productivity growth and the distribution of potential benefits and costs. Examples include climate change, food security and land use changes induced by rising biofuels production. Over the past half century or so, rising demand for crops and crop products have been met in large part by rising yields, not by large increases in area planted. The future of food prices and availability will depend on how yields respond to pressures associated with climate change, income growth and changing dietary patterns, and other factors that can affect hunger, rural incomes, and other societal objectives.

The theoretical and empirical literature relating to crop yield response suggests that economic agents, including farmers, input

suppliers and researchers, respond to market incentives. However, most of what scientists have learned about the magnitude of those responses characterizes only short-run adjustments. None of these studies seem to address adequately all the challenges to isolating short-run response to changes in market conditions, including the distinction between observed price fluctuations and expected prices, limited options for adjusting resource allocations in the short run and the likelihood that weather shocks dominate year-to-year yield changes. A review of empirical analyses reveals a general consensus that crop yield response to price is important, but very few studies attempt to estimate long-run yield response.

We rely on a theoretical basis and related literature estimating fundamental input supply and input demand elasticities to estimate long-run yield responses. Moreover, by relating input shares to economic development, we develop an approach that can be used to estimate the different responsiveness among countries or of a single country over an extended period of time. A practical result is that more developed countries where a greater share of inputs are purchased, rather than farm-owned, will tend to have greater long-run yield response. This analysis has two important implications. First, direct estimation of long-run yield response might be further complicated by the potential for this elasticity to vary over time. Second, long-run market analysis, including for food security or climate change, should take into account the scope for yield response to rise over time, such as by using the method developed here.

Our approach has several limitations. For example, we draw lessons from the literature, particularly on yield response to prices and the association of supply response to inputs shares, so persistent errors in these bodies of work would also affect our results. We develop our relationships from economic development to input shares and then from input shares to yields using data developed by others, such as the World Bank and the GTAP consortium, and from available literature, so the validity of these links necessarily depends in part on these choices. Agricultural cost share data, in particular, could be further investigated. Although we detect little difference among various functional forms we investigate for specifying these relationships, additional work could test different data sources and different specifications. Additional work could consider other food policy topics in light of our findings, include other important food crop supply and demand drivers, or consider how various published projections of market conditions and prices could be reassessed with full, long-run yield response included.

Results highlight substantial differences in market outcomes, and therefore, policy implications. As expected, price adjustments absorb the greater share of market response in the short run, due to mostly inelastic supply and demand responses. Those early price effects are substantially moderated in the long run partly due to higher yield elasticities. Policy reactions focusing on the immediate price effect of a sustained market shock might be seen as over-reactions if assessed in light of the long-term price effects after a greater yield response, perhaps particularly if those policies target future crop supply or food demand. For example, if policies cause publicly funded research and development to surge when prices are high, then the delayed yield and research effects might be procyclical factors that together exacerbate price swings.

Many other policy questions are tied to yield response. Past authors have identified the importance of yield in determining crop market effects of biofuels and these results concur with ours. However, the correspondence of greater yield response and greater share of energy inputs in cereal production costs implies that an expectation of higher yield response to biofuel demand can be accompanied by greater supply response to energy prices. A high energy price context that might make biofuels more attractive to consumers can also mean high yield responses, but the timeframes of these effects are different and lead to a price surge followed by steady mitigation of that price shock. The implication of biofuels for prices can be further complicated if their impact on broader fuel markets and prices feedback to agricultural production costs. In all cases, policy implications are contingent on a country's level of development, which correlates with yield response, and trade policy. A developing country that is not integrated with world markets will have neither as much domestic yield response as most other countries nor access to global supplies, suggesting a greater possibility of strong price sensitivity over time with respect to demand or other market drivers. In contrast, prices in developing countries that are integrated with world markets will tend to be more stable with respect to changes in domestic market conditions, so sustained access to global yield response might help support some food policy objectives over time.

The empirical results highlight the scope for greater yield response to mitigate a price shock, but also the potential that higher yield response is accompanied with greater shares of inputs and, consequently, the scope for more external factors to play a larger role in driving cereal markets in the future. As regards the potential that sustained income growth drives crop price inflation in the future, this risk abates if long-run response to yields is recognized as the primary source of future crop supply increases. Thus, our results show that the potential for yield response to input and output prices is critically important for long-run food policy and market analysis.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodpol.2018.12.001.

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